A quasioptical steering system for the CCAT/XSPEC submillimeter multi-object spectrometer

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ABSTRACT

A two arm, opto-mechanical positioner mechanism is presented in this proceedings as a candidate steering system for the millimeter-wave XSPEC spectrograph. The design is well matched to the expected target density on the sky, and meeting all requirements of the Cerro Chajnantor Atacama Telescope (CCAT), site environmental conditions (e.g., operating temperature and power dissipation), and the positioning requirements themselves for acquiring and tracking astronomical objects whose light is fed into the XSPEC spectrograph units. The prototype design has been fabricated and tested for basic operations.
Keywords: Galaxies, cosmology, spectrometer, opto-mechanics

1. INTRODUCTION

For observations in the (sub-)millimeter of extragalactic sources, signal strengths are generally low, so that long integration times are necessary. This means that there is considerable value in observing multiple sources simultaneously. However, the density of detectable sources on the sky is modest, even for a telescope with relatively large collecting area like CCAT. Thus, to exploit a focal plane array for survey mode spectroscopy, we will be observing sources spread across the instantaneous field of view of the telescope, and ideally should be able to match the positions of the array pixels in the focal plane to the positions of the sources of interest which will have been identified and located by less time consuming continuum surveys.

Goldsmith & Seiffert (2009) [1] presented a conceptual design for the input optical system for a multi-object spectrometer operating at submillimeter wavelengths. The "Mirror MOS" is based on a sequence of mirrors that enables low-loss propagation of beams from selected positions distributed throughout the focal plane to the spectroscopic receiver inputs. This approach should effectively mitigate the inefficiency of using an "IFU" array receiver with uniformly spaced, relatively closely packed beams, which would have a much higher cost in detectors and readout, and would have substantial "dead-space" on the array with no detectable signal.

The Goldsmith & Seiffert [1] concept is based on assigning a patrol region to each of the receivers, which have inputs distributed over the focal plane of the telescope. The input to each receiver can be positioned at any point within this patrol region. This approach, with only 4 reflections, offers very low loss. The Gaussian beam optical system can be designed to produce frequency-independent illumination of the telescope, which is an important advantage for broadband systems such those required for determination of redshifts of submillimeter galaxies using CCAT.

2. DESIGN AND FIRST PROTOTYPE

2.1 Optical Design Context

An optical design for the positioner has been matched to the CCAT telescope optics, where we desire constant OPL over the patrol region: we want telescope focal plane **locally flat** and normal to MOS rotational axis. We desire fixed beam direction: we want telescope beams **locally aligned** to MOS rotational axis.

Because of the curved focal plane of CCAT, we can have Locally flat, or beams locally aligned to MOS axis, **but not both.** Aligning MOS to local focal plane is the best solution, removing the need for large piston (Fig. 4).

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For the optical design (Fig. 5), we want a
- compact system, requiring powered optics;
- broadband ($\lambda = 0.6 – 1.6$mm) performance, requiring Gaussian Beam Telescope;
- minimized M5 counter-rotation mirror/wedges, requires placing at CCAT focal plane;
- minimized entrance window, requiring that we form waist and MOS unit output;
- a cold lens following the steering system; vertical paths (EW – M1 and M1 – M3) set only by mechanical constraints and horizontal paths (M1 – M2 and M3 – M4) set by beam clearance.

2.2 Mechanical Design and Implementation

A mechanical design was developed to meet the needs of the optical design criteria above. By using commercial Aerotech stages for the two rotatory arms, the design can handily meet all mechanical needs, except for low temperature environment. Tests are underway (sec 2.5) to assess operations at the lowest temperature ranges.

Basic load estimations (Fig. 6) suggest the total torque for Stage 1 is near the nominal Aerotech stage limit. However precision testing (sec 2.5) shows that much heavier loads in practice do not degrade performance. The properties and load limits of the Aerotech stages are shown in Fig. 7, along with the mechanical design and the functioning prototype.

The M5 counter rotation mechanism was implemented with stepper motors and worm gears, with an optical encoder to track position, providing a low power solution for this low-torque application. While the system meets our design criteria, a more sophisticated system will be adopted for practical deployment and field testing.

The M3 chopping mirror is still under development. Both a voice coil solution and a stepper motor solution have been adopted in the prototype, and are under test as is discussed in sec 2.6.

Finite element analysis has been performed on the mechanical design, deriving resonant frequencies shown below under the assumption of no loads except gravity. The low resonant frequencies show that our mechanical design is adequate in terms of stiffness requirements, however the design was not optimized and will likely be implemented differently in practice.

2.3 Accuracy

The accuracy of the system was tested with an experimental setup using a laser run backwards through system, where the position of beam is measured on a large astronomical CCD. Tracking as slow as the sidereal speed on stages at field center (0.004 deg/sec) yields 0.06mm RMS below the 0.13mm RMS requirement (Fig. 8). Faster tracking speeds (off CCAT optical axis, or near zenith) deliver even higher precision. Much heavier loads than adopted here in practice do not degrade the performance. Nonetheless, higher torque motors could be used if deemed necessary for field implementation.

The optical encoder on the purchased Aerotech stages provides 0.15mm RMS positional measurement accuracy (but a different encoder is available that can do significantly better if required). The currently used encoder does not affect our tracking or centering accuracy.

2.4 Power Dissipation

We tested the power draw from motor and controllers using a Fluke 345 Clamp Meter in 3-phase mode. While the controllers draw 12W of power, the motors on the stages themselves draw significantly less than 1W in operating modes. The resolution of the Fluke meter is only 1W, and instantaneous power on the Aerotech stages is too low for accurate measurement. However, the time series average measurements produce repeatable measurements at the 0.25W level (Fig. 9). Power consumption when warm is an increasing function of speed, with only modest dependence on load. We see only small differences between loaded (prototype positioner setup) and unloaded (stages only). Significant additional loads are required to measure any larger power draw. (Note that such additional loads are achieved at cold <20 deg C temperatures due to friction in the system – 2.5).

2.5 Field serviceability, robustness, and cold testing

(i) Cold testing setup:

A cold environmental testing setup was adopted to allow the stages to be run continuously cold (<20 deg C) for several months in a dedicated freezer, to provide accelerated Chilean environment testing. A Fluke 345 power meter records power dissipation, and thermocouples record stage and ambient temperatures. The stages are double wrapped in plastic to minimize condensation, and two nested fridges are used: a dry ice inner container within the -30 deg C insulated freezer.
The Positioners travel 3600 deg at 0.1 deg/s then reverse, looped indefinitely; periodic fast moves at 10-90deg/s simulate reconfiguration. Thermocouples (type T and K) sample temperatures every 15 seconds, while the Fluke 345 Clamp Meter samples voltage, current and power factor every 15 sec. The freezer ambient temperature can reach -30 C and the dry ice nested container achieves -80 deg C.

(ii) Cold testing results:

Over the course of cold testing, a clear trend of power increase (~4 times room temperature) at low temperatures (<-20deg C ambient) is observed during cool down, running at 10deg/sec. (Fig. 11), which is likely a result of increased friction in the system. As the differential expansion of differing materials (Al, Cu, Brass) is estimated to be <1/1000" , the most likely reason for the friction may be the grease which begins to freeze at these temperatures. Low temperature grease or graphite lubricants should readily solve this problem.
The measurements of an immobile stage under fridge base temperature of -30 deg C reveals in fact that there is a danger of stages binding completely if cooled without running. Small motions at 0.1 deg/sec are then required (over ~30min) to warm it up before it will operate normally again. Fig. 11 shows the stage has effectively raised its internal temperature to -20deg and power draw then appears to be constant with time.

Using the dry ice fridge, we note that the stages being to perform poorly below -40 deg C, and fail completely by -50 deg C, even while running at 0.1deg/s. Testing of low temperature bearing/gear lubricants is underway, considering graphite, or DuPont Krytox, or Dow Molykote 33.

2.6 On-board sky chopper

Various mechanisms have been under investigation for an on-board chopper: voice coils, RC servo motors, and stepper motors. A 'toy chopper' was initially tested (voice coil carrying a diode, illuminated with a laser). Fig. 10 shows that 0.08 sec lost in 1Hz chop (duty cycle >90%), with an accuracy of <1deg (<1mm at end of chop arm), dominated by our experimental test setup. The requirement is 0.35deg.

A more robust voice coil (arc segment actuator, from Motran industries Inc.) has been implemented directly in the prototype, and demonstrates reasonable chop, running open loop with hard stops, and carrying lightweight mirrors. This may be a viable solution to problem, and we are further testing close loop positional feedback operation. Other mechanisms are being investigated as well.

2.7 Risks and Alternatives

The motor on Aerotech can be either a DC brushless servo or a stepper motor. While the stepper motor is less susceptible to stiction and simpler to control, we likely want a servo system so we are not running full power all the time (since during acquisition and peakup, our power draw is >10x that at tracking speeds.

While we are currently testing with an AC transformer / controller, Aerotech offers a scalable controllers run from a single DC power supply – this is better/cheaper for us, allowing us to run 10 or more stages off single power supply.

We have provided detailed feedback to Aerotech on the performance of their stages, and the space requirements of our designs. Aerotech has recently supplied a modified design AGR75-NC-9DU-BMS-R-3 which includes: a right angle gearbox (motor bent at 90deg, saving substantial space in the stage footprint, a Braycote low temperature grease in all gears, motor and gearbox, a modified motor shaft and include a low temperature encoder (-30 deg C to + 75DegC operating rated encoder), as well as mechanical modifications to help operations at lower temperatures.

2.8 Figures

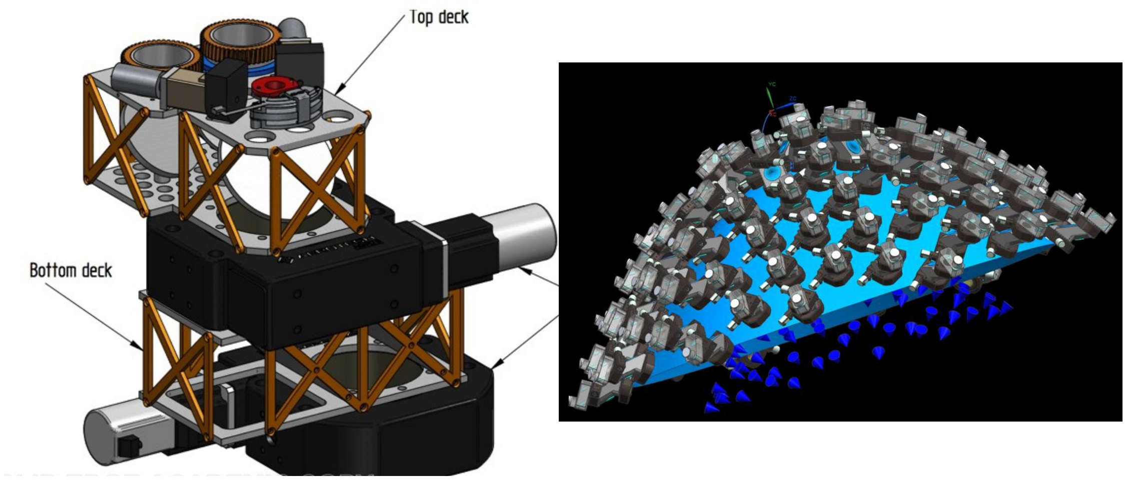

Fig. 1: A prototype positioner unit and a visualization of 100 units on the CCAT focal plane.

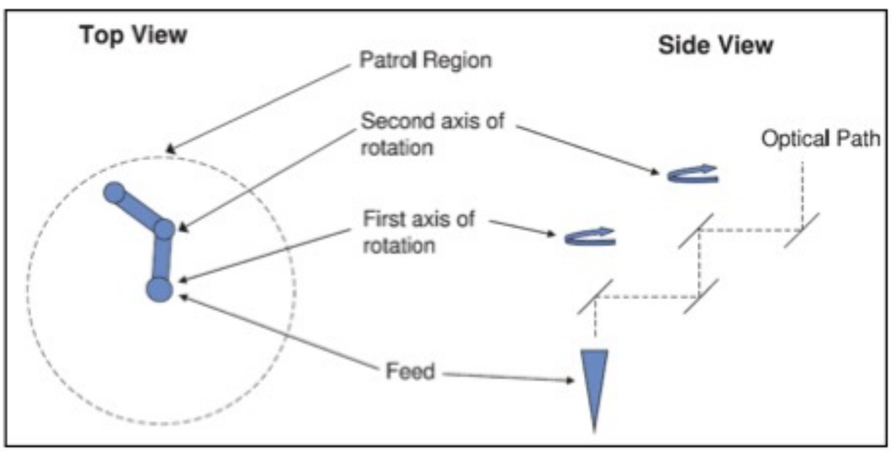

Fig. 2: Conceptual design (From Goldsmith & Seiffert 2009)

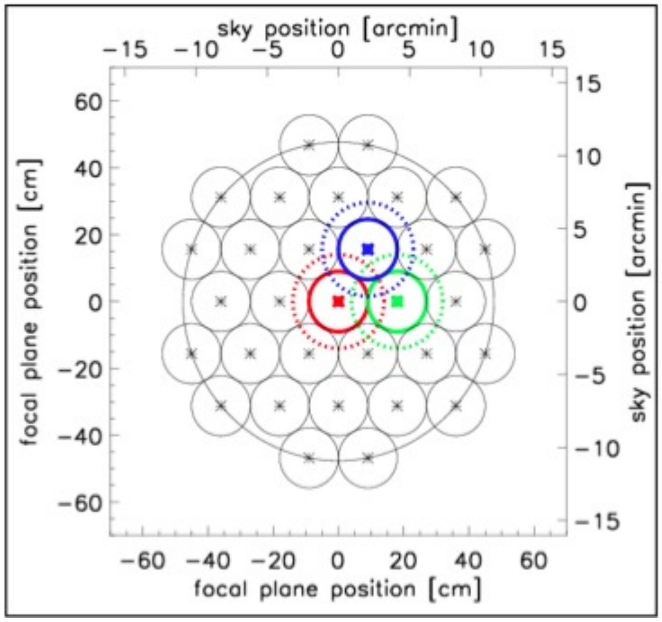

Fig.3: example 31 beam configuration of MOS steering system from Goldsmith & Seiffert (2009).

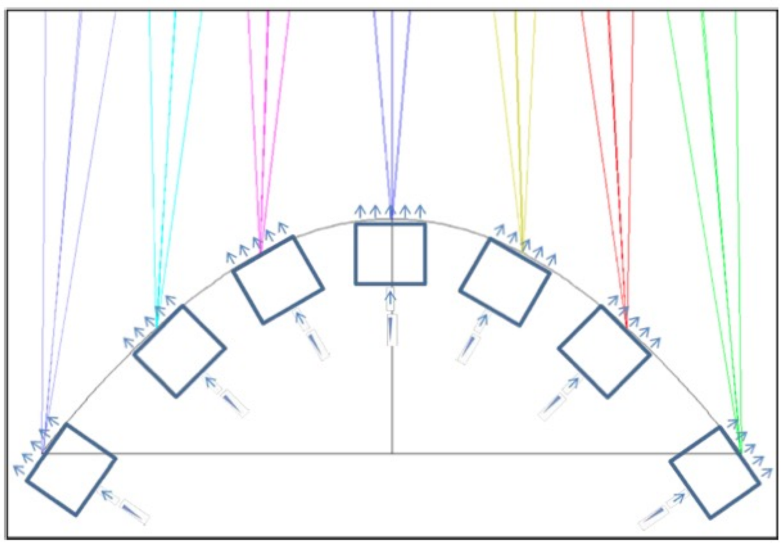

Fig. 4: MOS aligned to local focal plane, requiring a tilted mirror or wedge to direct beam through positioner (M5 in optical design).

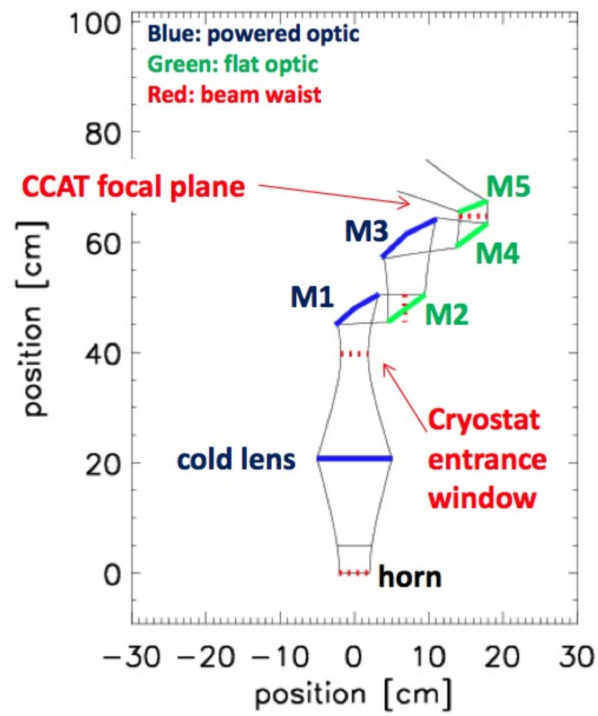

Fig. 5: optical design for steering system positioner unit.

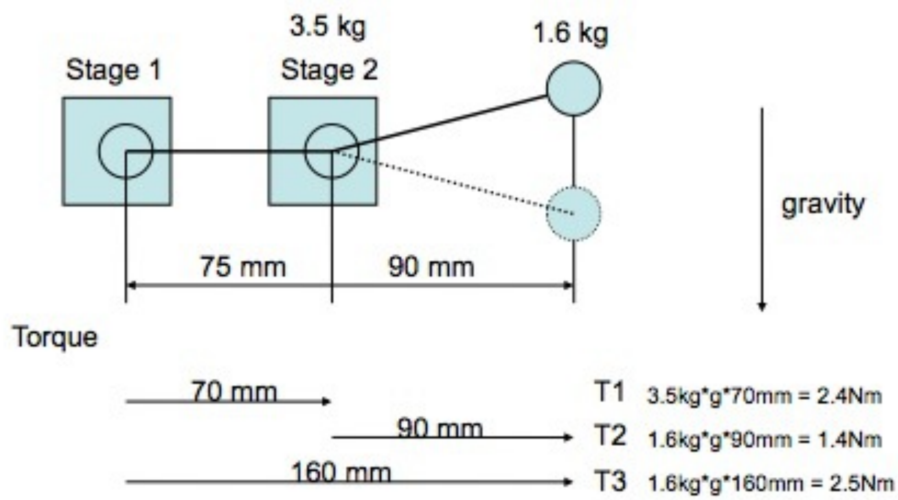

Fig. 6: Basic load estimations

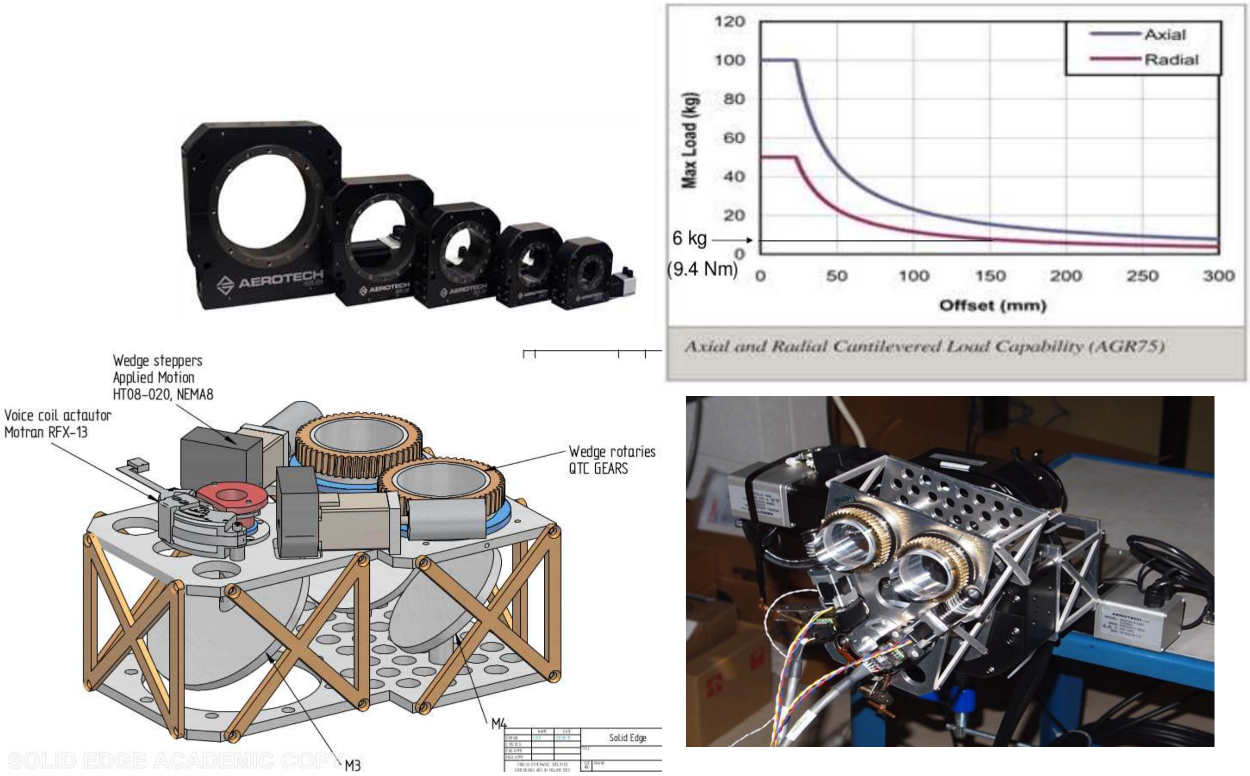

Fig. 7: Details of the commercial Aerotech stage line, the axial and radial load limits, and the mechanical design and implementation of the XSPEC positioner.

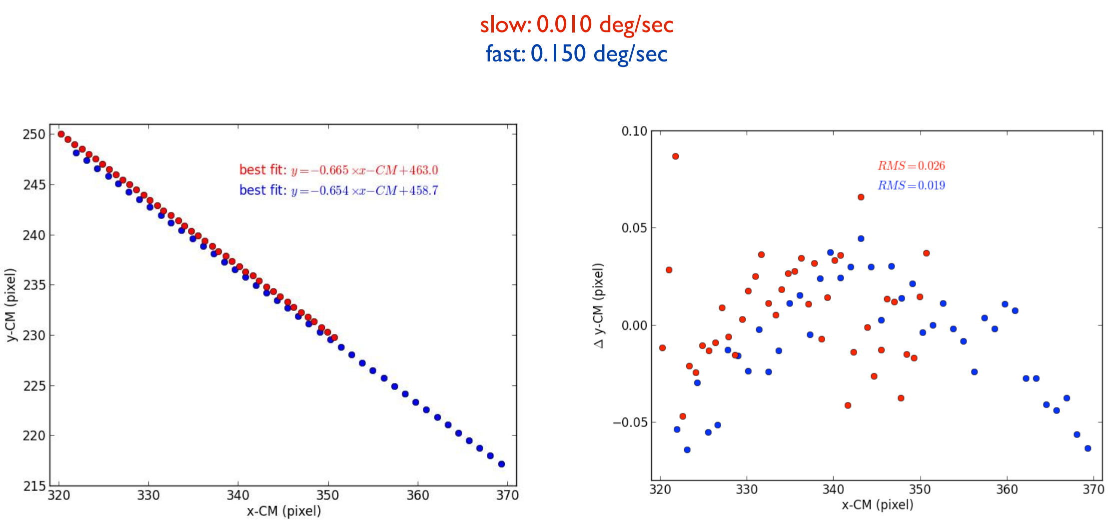

Fig. 8: Results of tracking accuracy test

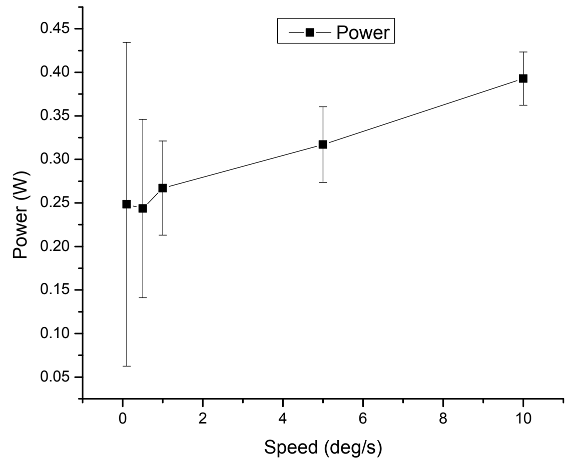

Fig. 9 Power draw on Aerotech motor as a function of rotation speed.

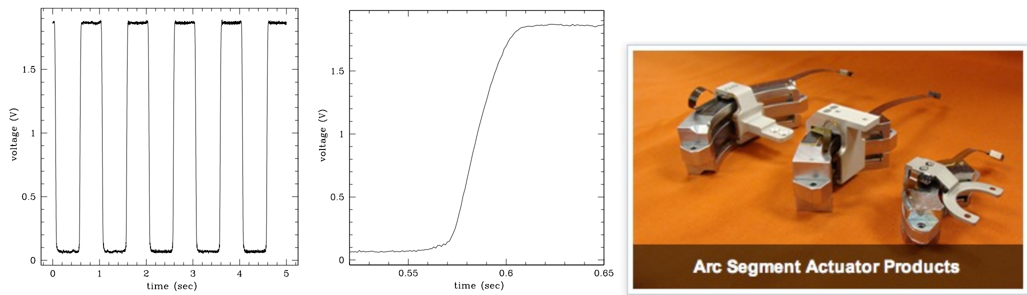

Fig. 10 (top) voice coil chopper (voice coil carrying only a diode) shows acceptable chop under light loads. (Below) The Motran voice coil, currently being tested in the prototype steering system.

2.9 Tables

Requirement	Value
Number of Elements	Maximize subject to FOV and spacing between centers
Patrol radius	> 14 cm (center of feed to center of M4), attempt to maximize
Field of View	3m = 1.0 deg
Spacing between element centers	2 * 12.124 cm (root3/2 * 14 cm)

Wavelength range	Design for CCAT Band 1 &2 (~185 – 550 GHz)
Beam Switching? Switch Speed Travel Modulation profile Dead time (time that we are neither on or off source)	Yes. 1 Hz requirement, 2 Hz goal 3-5 beams Square wave < 25% (for 3 Hz) settling time to 1/10 of a beam of 100 ms. 1/10 beam is 400 microns (gives 80% duty cycle at 1 Hz, 60% duty cycle at 2Hz)
Mapping mode for deep field?	Use telescope raster
Positioning accuracy	< 1/30 of a beam (<130 microns) [beam: 3.6 mm]
Field rotation sky tracking accuracy	< 1/30 of a beam, sufficient rate to guarantee this accuracy
Typical observation time per config	8 hours
Lifetime	> 10 years, operated at 50% of 16 hour nights duty cycle, with < 10% failure, refurbishment is okay.
Survival Temperature	-30 to +20 C
Operational Temperature	-10 to +20 C (TBC)
Ambient relative humidity	?
Power dissipation	<1W per unit
Optical alignment tolerance -	TBD, allow shimming in mounting steering system to cryostat
Time to reconfigure for next field	< 10 minutes
Optical alignment relative to cryostat mounting	< 0.1 mm, allow between cryostat and steering system upon assembly.
Relative alignment of mirrors in steering system	< 0.1 mm, To be confirmed.
Focal plane shape	Parabola?

REFERENCES

[1] Goldsmith, P.F. and Seiffert, M., [PASP], A Flexible Quasioptical Input System for a Submillimeter Multiobject Spectrometer, 121, 735-742 (2009).